# Formation and Radiation Acceleration of Pair Plasmoids Near Galactic Black Holes

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#### ABSTRACT

We study quantitatively the formation and radiation acceleration of electron-positron pair plasmoids produced by photon-photon collisions near Galactic black holes (GBHs). The terminal ejecta velocity is found to be completely determined by the total disk luminosity, proton loading factor and disk size, with no dependence on the initial velocity. We discuss potential applications to the recently discovered Galactic superluminal sources GRS1915, GROJ1655 and possibly other GBHs.

Subject headings: acceleration of particles – accretion disks – gamma rays: observations

#### 1. INTRODUCTION

The origin of relativistic jets from Active Galactic Nuclei (AGNs) remains one of the great challenges in astrophysics. Earlier Phinney (1982, 1987) concluded that radiation from the accretion disk is probably not responsible for accelerating the superluminal AGN jets with bulk Lorentz factors  $\Gamma \sim 10$  (Porcas 1987). When  $\Gamma \gg 1$ , the aberrated photons in the jet's rest frame comes from the forward direction against the jet motion, thus limiting the maximum  $\Gamma$  achievable to only a few, much smaller than the observed values.

Recently, observations of several Galactic black hole (GBH) candidates have revealed a causal relation between X-ray and radio flaring of the central object. In some cases, radio plasmoids were ejected relativistically away from the central sources following the x-ray flares (Mirabel et al. 1992, Mirabel & Rodriguez 1994, Hjellming & Rupen 1995). In two cases, GRS1915 (Mirabel & Rodriguez 1994) and GROJ1655 (Hjellming & Rupen 1995), the ejecta motions appear to be superluminal, resembling the superluminal AGN sources.

Motivated by the correlation of the ejection with the x-ray flux, energetics of the ejecta and the relatively small  $\Gamma \sim 2.5$ , we proposed in a recent paper (Liang & Li 1995) a scenario for the origin of the episodic ejections based on the standard inverse-Compton accretion disk paradigm (Shapiro et al. 1976). The idea is that episodic quenching of the (external and internal synchrotron) soft photon source to a level less than the internal bremsstrahlung flux superheats the innermost disk

to gamma ray temperatures (Liang & Dermer 1988, Wandel & Liang 1991, Pietrini & Krolik 1995). However, these gamma rays cannot all escape, if their source compactness ( $\propto$  gamma ray luminosity/source size, Svensson 1984, Zdziarski 1984) is too high. Instead most gamma rays are converted into pairs via photon-photon pair creation which will be further accelerated axially by the radiation pressure of the disk x-ray flux and attain significant terminal Lorentz factors in a bipolar outflow if the disk luminosity is sufficiently high. When the ejecta encounters the interstellar medium and develops shocks and turbulence it will convert the bulk kinetic energy into high energy particles, emitting the observed radio synchrotron radiation.

In this paper, we summarize some key results for pair plasma formation and their radiation acceleration by the disk photons for GBHs.

## 2. COMPACTNESS AND FORMATION OF PAIR PLASMOIDS

To study the formation of the pairs produced by  $\gamma\gamma$  and  $\gamma x$  collisions outside the disk, we assume a 2-zone Keplerian disk model depicted in Fig.1. We define  $r_{\gamma}$  as the boundary, interior (exterior) to which local bremsstrahlung flux is higher (lower) than the soft photon flux. Gamma rays are emitted by a superheated ion torus within  $r_{\gamma}$  (Rees et al. 1982, Liang 1990), The spectrum from this region is assumed to be a Comptonized bremsstrahlung + annihilation spectrum with  $T_{\gamma} \sim mc^2$  (Fig.1a, e.g. Zdziarski 1984, Liang & Dermer 1988, Kusunose & Takahara 1988). Exterior to  $r_{\gamma}$ , we assume that the disk x-ray flux has the standard inverse-Compton spectral shape (Fig.1b, Shapiro et al. 1976, Sunyaev & Titarchuk 1980). Using standard photon-photon pair production cross-section we compute the (angle-averaged) gamma ray pair-production depth  $\tau_{\gamma\gamma}$  as a function of photon energy due to collisions among gamma rays and between gamma rays and disk x-rays:

$$\tau_{\gamma\gamma} \simeq r_{\gamma} \int d\epsilon' n(\epsilon') \sigma_{\gamma\gamma}(\epsilon, \epsilon') f$$
(1)

where  $\sigma_{\gamma\gamma}(\epsilon,\epsilon')$  is the angle-averaged pair production cross-section (Gould & Schreder 1967), and  $\epsilon \equiv h\nu/511 {\rm keV}$ .  $n(\epsilon') = n_{\gamma}(\epsilon') + n_x(\epsilon')$  is the normalized photon spectral density evaluated at  $r_{\gamma}$ , and f is a fudge factor of order unity to incorporate various complex geometry and angle-dependent effects (e.g. photon intensity anisotropy and variation with path length along the line of sight, angular dependence of  $\sigma_{\gamma\gamma}$ , etc.). We calibrate f using sample numerical simulations (details to be published elsewhere). For given geometry and spectral shapes (cf. Fig.1),  $\tau_{\gamma\gamma}$  basically depends only on the gamma ray source global compactness  $l_{\gamma} = L_{\gamma}/r_{\gamma}/(3.7 \times 10^{28} {\rm erg/cm/s})$  (Svensson 1984, Zdziarski 1984). In Fig.2a we plot  $\tau_{\gamma\gamma}$  as functions of photon energy for various  $l_{\gamma}$  and  $T_{\gamma} \sim mc^2$ . In Fig.2b we plot the fraction of gamma rays that are absorbed into pairs as a function of  $l_{\gamma}$ . We have assumed that all pairs produced escape without re-annihilation in situ due to their high kinetic energy ( $\sim$  few hundred keV). This is a crude approximation but we estimate the error to be less than a factor of 2. The critical compactness at which  $\gtrsim 80\%$  of the gamma rays are

converted into escaping pairs is around  $l_{\gamma} \sim 100$  (with  $\gtrsim 2$  uncertainty), consistent with similar results found by others (Zdziarski 1995, private communications). To achieve  $l_{\gamma} \geq 100$ , Liang & Li (1995) show that the overall accretional luminosity  $L_0$  must be  $\geq 0.1 - 0.2$   $L_{edd}$ .

### 3. RADIATION ACCELERATION

Consider a plasma of electrons, positrons and some entrained protons directly above the black hole and along the axis of the disk, interacting with the disk radiation via only Compton scattering (cf. Fig.1). Assuming that protons, electrons and positrons are always co-moving (a cold jet),  $\gamma_p \equiv \gamma_e = \Gamma$ , and local charge neutrality is maintained  $(n_{e^-} = n_p + n_{e^+})$ , we can obtain the equation of motion for the jet (at height Z) as:

$$-\frac{d\Gamma}{dz_*} = \left(\frac{m_e}{m_{eq}}\right) \left(\frac{r_g \sigma_T}{\beta c}\right) \int d\epsilon \int d\Omega \ I_{ph}(\epsilon, \Omega) (1 - \beta \mu) \left[\Gamma^2 (1 - \beta \mu) - 1\right] + \frac{1}{z_*^2}$$
 (2)

where  $z_* = Z/r_g$ ,  $r_g = GM/c^2$ , and  $\mu = \cos\theta$ , the angle between the photon momentum and the z-axis, and  $I_{ph}(\epsilon,\Omega)$  is the spectral intensity seen by the jet (cf Fig.1, see O'Dell 1981, Phinney 1987 for previous results).  $m_{eq}$  is the equivalent mass of the particles  $= m_e + \frac{\zeta_p}{2-\zeta_p}m_p$  with  $\zeta_p = n_p/n_{e^-}$ , the fraction of proton loading. For  $\zeta_p = 0$ ,  $m_{eq} = m_e$  for a pure pair jet and for  $\zeta_p = 1$ ,  $m_{eq} = m_e + m_p$  for an electron-proton jet. In deriving equation (2), we have: (1) kept only the parallel (z) component due to the axial-symmetry of the system (though there will be a random orthogonal component); (2) used the angle-dependent differential Compton scattering cross section (in Thomson limit) and ignored the energy change (second order in scattered photon energy), but kept the momentum change (first order in scattered photon energy) for acceleration; (3) included the gravity pull on protons and leptons but neglected the radiation force on protons.

The (isotropic) spectral intensity at the disk surface can be approximated as:

$$I_{ph}(\epsilon) = \frac{1.68 \times 10^{32}}{\epsilon \exp\left(\frac{511}{80}\epsilon\right)} \left(\frac{L_0}{L_{edd}}\right) \frac{1}{M_{10}} \frac{1}{\mathcal{G}} r_*^{-3} \left(1 - \sqrt{\frac{6}{r_*}}\right) \left(\frac{1}{\text{cm}^2 \cdot \text{s} \cdot \text{sr}}\right)$$
(3)

where  $r_* = r/r_g$ ,  $M_{10} = M/10 M_{\odot}$  and  $\mathcal{G} = 18 \left(\frac{1}{r_{min}^*} - \frac{1}{r_{max}^*}\right) + 2 \left[\left(\frac{6}{r_{max}^*}\right)^{3/2} - \left(\frac{6}{r_{min}^*}\right)^{3/2}\right]$ . Here,  $r_{min}^*$  and  $r_{max}^*$  define the size of the disk from which the total luminosity is  $L_0$ , and we assume  $r_{min}^* = r_{\gamma}/r_g$ . We have used the observed spectrum of GRS1915 (Harmon et al. 1994), but results are insensitive to detailed spectral shape since it will be integrated away when putting into equation (2) and only the total flux from each radius matters since we are working in the Thomson limit (as emphasized by the referee). The  $\gamma$ -ray component from  $r < r_{\gamma}$  (Fig.1a) produces negligible additional effects on the axial acceleration due to the strong  $\gamma - \gamma$  self-absorption at high  $l_{\gamma}$ . Substituting equation (3) into equation (2) the integral over  $\Omega$  becomes an integral over  $r_*$  (cf. Fig.1).

Equation (2) can be evaluated numerically for the terminal  $\Gamma_{\infty}$ . A key term in this equation is  $\Gamma^2(1-\beta\mu)-1$ , which signifies the accelerating (or decelerating) force from a "ring" of radiation at radius  $r_*$ , depending on whether it is negative (or positive) for particles at the height  $z_*$ , where  $\mu=z_*/\sqrt{z_*^2+r_*^2}$ . One can find a disk radius  $r_{sep}$ , interior to which disk radiation accelerates the ejecta, and exterior to which radiation decelerates the ejecta. Whether an ejecta can get net acceleration depends on the sum of these two contributions.

The dependence of  $\Gamma_{\infty}$  on the initial conditions ( $\Gamma_{initial}$  and  $z_{min}^*$ ) and the geometry ( $r_{min}^*$  and  $r_{max}^*$ ) can be obtained by solving equation (2). We will focus on cases with  $\zeta_p = 0$  first. The results are shown in Figure 3 and summarized here.

- (A). For fixed disk geometry and total disk luminosity, regardless of their initial velocities  $\Gamma_{initial}$ , leptons will be accelerated to a fixed terminal  $\Gamma_{\infty}$ , even though particles with high  $\Gamma_{initial}$  get decelerated first. The radiation field acts like a "thermostat" that regulates the particle's final velocity along the z-axis. In Fig.3a, we show the ejecta's  $\Gamma$  as a function of height  $z_*$  with different initial velocities, whereas fixing  $r_{min}^* = 12$ ,  $r_{max}^* = 10^4$ ,  $z_{min}^* = 10$  and  $L_0/L_{edd} = 0.2$ .
- (B). Fig.3b, 3c, and 3d show the ejecta's  $\Gamma$  as a function of height  $z_*$  with different  $r_{min}^*$ , different  $r_{max}^*$  and different initial  $z_{min}^*$ , respectively. Again,  $L_0/L_{edd}=0.2$ . It is evident that,  $\Gamma_\infty$  depends somewhat sensitively on  $r_{min}^*$  since it is mostly the inner disk radiation that accelerates the ejecta; on the other hand, the dependence on  $r_{max}^*$  is weak as long as it is  $\gg 100$  due to the radiation intensity drops down drastically as  $r^*$  increases. Note from equation (2) that the rate of acceleration is proportional to  $d\Omega I_{ph}(\epsilon,\Omega)$ , which is decreasing as  $1/z_*^2$ . So efficient acceleration only occurs within a height of  $100-1000r_g$  of the black hole if the conditions are favorable.  $\Gamma_\infty$  is not a sensitive function of  $z_{min}^*$  as long as  $z_{min}^* \leq 50$ . Ejecta starting at very high  $z_*$  is not of interest here.

Our main results are summarized in Figure 4, where we show the terminal  $\Gamma_{\infty}$  as a function of  $L_0/L_{edd}$  for different proton loading  $\zeta_p = n_p/n_{e^-}$  with  $r_{min}^* = 12$ ,  $r_{max}^* = 10^4$  and  $z_{min}^* = 10$ . It is evident that for  $\zeta_p > 10^{-3}$ , gravitational attraction on the protons hinders the acceleration. This has important implications for the composition of the ejecta. If the jets are composed of pure pairs as suggested in previous sections, then radiation acceleration can indeed account for the observed  $\Gamma$  in both GRS1915 and GROJ1655 (Mirabel & Rodriguez 1994, Hjellming & Rupen 1995). The observed  $\Gamma \sim 2.55$  of GRS1915 implies  $L_0/L_{edd} \sim 0.2$ . This constrains the mass of black hole in GRS1915 to  $\sim 12M_{\odot}$  when using the observed luminosity (Harmon et al. 1994).

The jet could be suffocated if there is an additional isotropic radiation field  $I_{iso}$  and it reaches  $\sim 10\%$  of  $I_{disk}$ .  $I_{iso}$  could be caused by the companion wind or circumstellar medium.

#### 4. DISCUSSIONS

The pairs are born with average kinetic energy of several hundred keV. However, we do not expect the "Compton rocket" effect (O'Dell 1981) to be important to affect the ejecta's terminal velocity because the disk radiation field will regulate the particle's final velocity, no matter what the initial velocity is, as shown in Fig.3a.

We predict that the terminal  $\Gamma_{\infty}$  should increase as  $L_0/L_{edd}$  increases. This can be tested using the ejections from different episodes with the corresponding radiation luminosities.

To summarize, in the present approach, we have adopted the thermal accretion disk model for the hard x-ray emissions (as suggested by the spectra of GRS1915, Harmon et al. 1994), and use that as the basis for the pair production and bulk acceleration. Hence the energetics of the jet is constrained by the pre-ejection accretional X-ray power output (Liang & Li 1995). We find that, for a jet composed mostly of leptons, disk radiation can accelerate it to a terminal Lorentz  $\Gamma_{\infty}$  of a few, depending on the total disk luminosity and geometry. However, non-thermal processes may be needed to explain the power-law hard X-ray spectra of some x-ray novae (including GROJ1655, Harmon et al. 1994, Kroeger et al. 1995). Yet both classes of GBHs show relativistic outflows. Can GBH jets be also generated by say, purely electrodynamical processes unrelated to the conventional thermal hard x-ray disk models? We will explore alternative models in future publications.

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- Fig. 1.— Schematic depiction of the accretion disk along with emissions from the inner region (spectrum (a)) and the outer disk (spectrum (b)). At high compactness, spectrum (a) is not visible at infinity since most of it is converted into pairs within the dashed sphere. These pairs are then pushed out by the disk radiation with Lorentz factor  $\Gamma$  along the axis of the disk.
- Fig. 2.— (a) Pair-production optical depth  $\tau_{\gamma\gamma}$  as a function of photon energy. Curves a, b, and c are for compactness  $l_{\gamma} = 12$ , 100, and 392, respectively; (b) The fraction of gamma rays that are absorbed  $f_{abs}$  as a function of  $l_{\gamma}$ . Note that  $f_{abs} \sim 80\%$  for  $l_{\gamma} = 100$ .
- Fig. 3.— Ejecta  $\Gamma$  as a function of height  $z_*$  as solutions to equation (3) with  $L_0/L_{edd}=0.2$  and  $\zeta_p=0.0$  (pure pair jet). Parametric dependence of  $\Gamma$  on initial velocity  $\Gamma_{initial}$ ,  $r_{min}^*$ ,  $r_{max}^*$  and  $z_{min}^*$  are shown in plot (a), (b), (c) and (d), respectively. In each plot, other than the parameter that is varying, the rest are chosen from  $\Gamma_{initial}=1$ ,  $r_{min}^*=12$ ,  $r_{max}^*=10^4$  and  $z_{min}^*=10$ .
- Fig. 4.— The ejecta's terminal  $\Gamma_{\infty}$  as a function of  $L_0/L_{edd}$  for different proton loading  $\zeta_p = n_p/n_{e^-}$ . Curves a, b, c, d, e correspond to  $\zeta_p = 0.0$  (pure pair),  $10^{-3}, 10^{-2}, 10^{-1}, 1$  (e p jet). The insert corresponds to the vertical cuts for  $L_0/L_{edd} = 0.25, 2.5$  and 25, respectively. The observed  $\Gamma$  for GRS1915 is  $\sim 2.55$ .

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